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Improvements in the Rotorcraft Fuel Economy and Environmental Impact through Multiple-Landing Mission Strategy

Fakhre Ali[§], Ioannis Goulos, Vassilios Pachidis
Centre for Propulsion Engineering, School of Aerospace, Transport and Manufacturing,
Cranfield University, Bedford, United Kingdom.

ABSTRACT

This paper presents an integrated rotorcraft multidisciplinary simulation framework, deployed for the comprehensive assessment of combined rotorcraft–powerplant systems performance at mission level. The proposed methodology comprises a wide-range of individual modelling theories applicable to rotorcraft performance and flight dynamics, gas turbine engine performance, and estimation of gaseous emissions (i.e. nitrogen oxides, NO_x). The overall methodology has been deployed to conduct a comprehensive mission level feasibility study for a twin-engine light (TEL) rotorcraft, modeled after the Airbus Helicopters Bo105 configuration operating on a multiple-landing flying (MLF) mission approach compared to rotorcraft employing a conventional flying (CF) mission approach. The results of the analyses allow mission level assessment of the both aforementioned approaches for a wide-range of useful payload (UPL) values, mission range as well as mission level outputs (e.g. fuel burn, mission time, and gaseous emissions i.e. NO_x). Furthermore, evaluation of engine cycle parameters (i.e. overall pressure ratio (OPR), turbine entry temperature (TET), and engine mass flow) are also carried out with respect to both approaches. The results acquired through the parametric analyses suggest that the MLF mission approach has the potential to significantly reduce rotorcraft mission fuel burn as well as gaseous emission (i.e. NO_x). It has also been established through the acquired results that rotorcraft employing the MLF mission approach requires lower engine operating power throughout the entire mission duration, and therefore operates on a relatively lower engine OPR, combustor entry temperature, mass flow, rotational speed, and the TET compared to rotorcraft employing CF mission approach. It is emphasized that such operation of the engine can potentially improve the rate at which the engine components (i.e. compressor, combustor, and turbine) may deteriorate, thus the MLF mission approach can potentially provide further benefit in terms of engine maintenance and overall engine life. Finally it has been emphasised that the mission total range is a critical parameter in determining the level of benefit that can be attained from the employment of MLF mission approach.

NOTATION

Roman symbols

CO_2	Carbon dioxide
NO_x	Nitrogen oxides
$\dot{W}$	Engine mass flow, kg/sec

Greek Symbols

ΔMFB	Delta mission fuel burn, %
ΔNO_x	Delta nitrogen oxides, %

Acronyms

ACARE	Advisory Council for Aeronautics Research in Europe
CO	Carbon monoxide
CF	Conventional Flying
DP	Design Point
EMS	Emergency Medical Service
EW	Empty Weight, kg
FB	Fuel Burn, kg
FRV	Fuel Reserve, kg
HECTOR	HeliCopTer Omni-disciplinary Research-Platform
MLF	Multiple-Landing Flying
MFB	Mission Fuel Burn, kg
MDAO	Multidisciplinary Design Analysis and Optimization
NASA	National Aeronautics and Space Administration
NDARC	NASA Design and Analysis of Rotorcraft
NPSS	Numerical Propulsion System Simulation
OEW	Operational Empty Weight, kg
OW	Operational Weight, kg
OD	Off-Design
OPR	Overall Pressure Ratio
SFT	Standard Fuel Tank, kg
TEL	Twin Engine Light
TEM	Twin Engine Medium
TET	Turbine Entry Temperature, K
UAVs	Unmanned Arial Vehicles
UHC	Unburned Hydrocarbons
UPL	Useful Payload, kg
WGS84	World Geodetic System 1984

INTRODUCTION

Background

Simulation of operational performance and mission analysis has always been an important topic for the rotorcraft industry. These topics are now raising even more interest as aspects related to chemical emissions and ground noise impact, gradually gain increasing importance for environmental and social impact assessments (Ref. 1).

Rotorcraft activities presently amount to roughly 1,500,000 flight hours per year only with respect to European airspace. These represent an annual consumption of the equivalent of 400,000 tons of aviation fuel. Maintaining current rotorcraft technologies is expected to quadruplicate this figure within the next 20 years, this being a direct result of the anticipated traffic augmentation (Ref. 2). The Advisory Council for Aeronautics Research in Europe (ACARE), in an attempt to manage the environmental impact of civil aviation, has set a number of goals *(flightpath 2050)* to be achieved by the year 2050 (Ref. 3). These goals include, reduction of produced carbon dioxide (CO_2), nitrogen oxides (NO_x) and noise emissions by the order of 75% and 90% and 65%, respectively.

Maintaining current design and operational technologies is expected to quadruplicate the aforementioned figures within a time-frame of approximately 20 yr. This is a direct outcome of the anticipated traffic augmentation (Ref. 2). The rotorcraft community has to respond in a pro-active manner before environmental considerations present themselves as limiting factors considering the anticipated growth of civil operations. Hence, the current focus is to come up with optimum operational procedures as well as novel rotorcraft designs that will allow the realization of long-term sustainable operations as well as to limit their associated environmental impact to levels considered acceptable in terms of legislation, financial, and public concerns.

The rotorcraft operations resulting from civil and military operations, although comprising a significantly smaller portion of the aircraft market in comparison with the fixed-wing aircraft, are experiencing the same concerns with respect to the amount of gaseous emissions produced. The rotorcraft plays a specific and inimitable role in air transportation and it is often used for purposes where the environmental concerns are secondary, (e.g. Medical Rescue operations, Law Enforcement, Search And Rescue, Fire Suppression, Surveillance, Military Combat and Transport purposes). However, the rotorcraft traffic related to passenger transport/air taxi requirements that up to now has been marginal, is expected to grow rapidly in the near future (Ref. 2). This is mainly driven by the exponential growth in passenger air travel demand that is foreseen for the 2015 – 2020 period (2 to 3 fold increase) (Ref. 2).

Clarke et al in Ref. 4 described three potential paths towards limiting the environmental impact of civil aviation:

i. Significant reduction in the number of operations.
ii. Incorporation of innovative and more efficient airframes and innovative powerplants.
iii. Deployment of alternative operational procedures: the seeking of optimal flight paths.

Option (i) is not a feasible direction due to the aforementioned forecasted expansion in air traffic (Ref. 2). With regards to option (ii), the associated time scale to commercialise new configurations from the conceptual stage along with all the required airworthiness certifications can reach up to 50 years, as elaborated in (Ref. 5). Thus, in order to address the targets set by ACARE for the year 2050, emphasis needs currently to be placed towards the design of optimum operational procedures. Furthermore, it is to be noted that, a simultaneous investigation of novel designs must also be deployed in conjunction with option (iii) in order to effectively address the long-termed ACARE goals. Therefore, in order to effectively manage the long-term environmental impact of civil aviation while simultaneously accounting for the expected traffic growth, both options (ii) and (iii), need to be thoroughly explored.

Rotorcraft-engine design optimization

With regards to option (ii) as elaborated by Goulos et al in Ref. 6, the overall approach can effectively be subcategorized within two major sectors of aerospace related research; airframe–rotor design, and engine cycle optimization. With respect to the latter approach related to rotorcraft applications, Goulos et al in Ref. 6 proposed a methodology- Helicopter Omni-disciplinary Research Platform (HECTOR) with the potential to reduce fuel consumption associated with the civil rotorcraft operations at mission level, through optimisation of the engine design point cycle parameters.

The design space variables essentially comprised the overall Pressure Ratio (OPR), total engine mass flow ($\dot{W}$), and Turbine Entry Temperature (TET). Their results, through a multi-objective optimisation achieved an increase in maximum take-off power as well as a reduction in fuel consumption of the order of 28% and 10% respectively, for a TEL-EMS mission, relative to the baseline case and an increase in design point shaft power and a reduction in mission fuel burn of the order of 11% and 8% respectively, for a TEM-SAR mission, relative to the baseline.

Alternative engine conceptual design and analysis

Another available approach that can effectively lead towards the enhancement of the current rotorcraft engine technology is through the implementation of advanced cycle engines that are much more efficient than the conventional Brayton cycle (Simple Cycle) engines. Considering unprecedented improvements in engine fuel efficiency, the most promising candidate is the advanced regenerative turboshaft concept. Rosen in Ref. 7 elaborated "the UAVs or helicopters that are intended for extremely long duration missions may require powerplants that are much more efficient than Brayton cycle gas turbine engines". Also Saravanamouttoo in Ref. 8, when discussing regenerative technology, suggests "it is not impossible that regenerative units will appear in the future, perhaps in the form of turboshaft engines for long endurance helicopters".

Ohanian et al in Ref. 9 deployed a multidisciplinary optimisation framework for the conceptual design and analysis of advanced alternative engine architectures (e.g. regenerated, intercooled regenerated) for rotorcraft applications. Their study was based on the integration of NASA Design and Analysis of RotorCraft (Ref. 10) (NDARC) and Numerical Propulsion System Simulation (Ref. 11) (NPSS) coupled with the OpenMDAO (Ref. 12) package. The integrated framework was deployed to perform a design space exploration study for a TEM multipurpose helicopter based on the BK117 B-2 helicopter configuration, operating under a generic Search And Rescue mission. The acquired results from their optimised engine designs suggested substantial improvements in the mission payload-range capability of the helicopter. For the recuperated helicopter configuration with a gross weight of 2800 kg, a 50% improvement in mission fuel burn was realized compared to baseline simple cycle engine.

Ali et al in Ref. 13 conducted a comprehensive preliminary trade-off study through the implementation of a multidisciplinary design framework (HECTOR). Their study was based on an existing TEL multipurpose rotorcraft configuration employing conventional engines and sub-optimum conceptual regenerative engines. Their results acquired through the implementation of a representative case study suggested that, the acquired sub-optimum regenerative engine design with a HE effectiveness of 60%, has the potential to offer a 34% reduction in mission fuel burn, a 34% reduction in mission CO_2 inventory, however, results in almost two times higher mission NO_x inventory compared to reference simple cycle engine. Their study concluded that, "conceptual regeneration configuration has the potential to significantly improve the CO_2 emissions through the reduction in mission fuel burn, however it may have a detrimental effect on the mission emissions inventory level, specifically for NO_x, imposing a trade-off between the fuel economy and environmental performance of the rotorcraft".

To further quantify the aforementioned regenerative engine design trade-offs. Ali et al in Ref. 14 extended the HECTOR implementation to perform the preliminary design of an optimum conceptual regenerative engine. Their work employed a single-objective particle swarm optimizer to conduct three single-objective optimization studies. Their acquired results suggested that designing an engine to attain minimum mission fuel burn requires an engine design that corresponds to maximum attainable thermal efficiency. However, on the other hand minimization of mission NO_x inventory requires an engine design with the lowest possible thermal efficiency, highlighting the trade-off between the mission fuel burn and NO_x emissions.

Following the successful implementation of single-objective optimization analyses, Ali el al in Ref. 15 further expanded the design effort and implemented a multi-objective optimization strategy within HECTOR to quantify the trade-off between mission fuel burn and NO_x emissions. The most promising configuration acquired through the multi-objective optimization (Pareto front model) offered 36.02% increase in rotorcraft range capability (at mission cruise conditions), 7.3% reduction in mission NO_x inventory, while it increased the initial all-up-mass (AUM_i) of the rotorcraft by $\approx$1.7% compared to the sub-optimum baseline engine.

Rotorcraft mission profile management and trajectory optimisation

To address option (iii) several initiatives are underway specifically in Europe under the Seventh Framework Programme of the European Community. Aircraft flight trajectory optimisation studies corresponding to both fixed and rotary wing aircraft are being explored, aiming towards lower overall mission fuel burn, emissions and noise levels. Goulos et al provides a brief evaluation of the related literature in their study (Ref. 16). Their work was focused on the simulation and multidisciplinary optimisation of complete, three-dimensional rotorcraft operations for fuel burn, chemical emissions, and ground noise impact. Their investigated case studies suggested a potential reduction in total mission fuel consumption of the order of 20% and 7% for a police and a passenger transport operation, respectively, relative to their corresponding suboptimal baselines. Also, Lawson et al in Ref. 17 deployed a multidisciplinary optimisation framework for minimum rotorcraft fuel burn and air pollutants at mission level.

Their work included single and multi-objective optimisations for mission block fuel burn, CO, UHC and NO_x emissions. Their acquired single objective optimisation results based on a generic representative mission profile suggested a reduction in mission block fuel burn of the order of 3.35% in exchange for a 2% trade-off in mission block NO_x emissions. Their multi-objective optimisation studies also suggested a reduction in mission block fuel burn of the order of 2% and up to 4.7% decrease in mission time, and CO and UHC emissions, followed by a negligible increase of 0.1 % in mission block NO_x emissions.

Scope of present work

In light of the aforementioned background and research dedicated towards addressing option (ii) and (iii). It can be realized that HECTOR has been successfully deployed to implement studies related to the exploration of optimum rotorcraft conceptual designs as well as towards the assessment of integrated rotorcraft-powerplant systems at mission level. This study aims to extend the research and application of HECTOR with regards to addressing option (iii), by conducting a comprehensive mission level feasibility study for rotorcraft operating on a Multiple-Landing Flying mission approach (MLF) compared to rotorcraft employing a Conventional Flying (CF) mission approach.

An integrated multidisciplinary rotorcraft simulation framework (HECTOR) has been deployed, the implemented methodology comprises a wide-range of individual modeling theories applicable to rotorcraft flight dynamics, gas turbine engine performance as well as a physics-based, stirred reactor model for the rapid estimation of various rotorcraft emissions species. The overall methodology has been applied to conduct a mission level feasibility study for a twin-engine light rotorcraft, modeled after the Airbus Helicopeters Bo105 configuration, simulated under the representative mission scenarios.

Detailed mission level assessment is presented between the rotorcraft operating under the MLF mission approach with the rotorcraft following a CF mission approach. The results are acquired by conducting a comprehensive parametric analyses. The results of the analyses allow mission level assessment of the both aforementioned approaches for a wide-range of Useful Payload (UP) values, mission range as well as mission level outputs e.g. fuel burn, mission time, and gaseous emissions i.e. NO_x. Furthermore, evaluation of engine cycle parameter (i.e. OPR, TET and $\dot{W}$) are also carried out with respect to both approaches.

The results acquired through the parametric analyses suggest that the MLF mission approach has the potential to significantly reduce rotorcraft mission fuel burn as well as gaseous emission i.e. NO_x. Furthermore, it has been established through the results that for a representative TEL rotorcraft operating with 100% payload on a single-leg mission (A to B) with a range of 300nm. The employment of MLF mission approach can potentially reduce the mission fuel burn and NO_x emissions by the order of 4.65% and 7.97% compared to rotorcraft operating under CF mission approach. The aforementioned benefit is however realized in exchange for a trade-off in mission total time of the order of (7.33 minutes OR 4.5%), imposed due to additional mid-point landing procedure associated with MLF approach.

The acquired results also suggest that rotorcraft employing the MLF mission approach requires lower engine operating power throughout the entire mission duration, and therefore operates on a relatively lower engine OPR, combustor entry temperature, mass flow, rotational speed and the turbine entry temperature compared to rotorcraft employing CF mission approach. It is highlighted that such operation of the engine can potentially improve the rate at which the engine components (compressor, combustor, and turbine) may deteriorate, thus can potentially proof further benefit in terms of engine maintenance and overall engine life.

Finally it has been emphasised that the mission total range is a critical parameter in determining the level of benefit that can be attained from the employment of MLF mission approach. The proposed methodology constitutes an enabling technology for the evaluation of existing and conceptual rotorcraft, in terms of operational performance and environmental impact at mission level.

SIMULATION METHODOLOGY

Integrated rotorcraft multidisciplinary simulation framework

This study requires the deployment of an integrated multidisciplinary rotorcraft simulation framework. The methodology deployed for the simulation of complete rotorcraft operations herein comprises a series of dedicated numerical formulations, each addressing a specific aspect of rotorcraft flight dynamics, engine performance and computation of mission emissions inventory. The proposed simulation methodology herein comprises the Lagrangian rotor blade model analysis presented in (Refs. 18 -19), a flight path profile analysis based on the World Geodetic System dated in 1984 (WGS 84) (Ref. 20), a non-linear trim procedure solving for the aeroelastic behaviour of the main rotor blades as described in (Ref. 21), an engine performance analysis model and gas turbine emissions model as detailed in (Refs. 22-23).

Each of the aforementioned modeling methods is integrated together within a standalone framework under the name “HECTOR” presented in Fig.1. HECTOR is capable of simulating complete, three-dimensional rotorcraft missions using a fully unsteady aeroelastic rotor model. HECTOR has been extensively described in (Refs. 21, 23-24), therefore only a brief description of the associated models is provided in this paper.

Engine Performance Simulation (TURBOMATCH)

The engine modelling and performance simulation code (TURBOMATCH) employed for the simulations carried out in this study is a Cranfield University in-house code, developed over a number of decades (Ref. 25). TURBOMATCH has previously been utilised in several studies available in the literature for the prediction of Design Point (DP) and Off-Design (OD) performance of gas turbine engines (Refs. 22, 26). In order to comply with the scope of work presented in this paper, the engine is assumed to be operating at steady-state OD conditions throughout the mission.

Prediction of Gaseous Emissions (HEPHAESTUS)

In order to predict the gaseous emissions arising from the fossil fuel combustion in the combustion chamber, the deployment of a robust prediction methodology is necessary. To satisfy this need, a generic emission indices calculation software has been adopted with the integration of HEPHAESTUS, developed by Cranfield University.

HEPHAESTUS provides a general prediction methodology based on the stirred reactor concept along with a set of simplified chemical reactions. HEPHAESTUS is capable of accounting for differences in the combustion system. Thus the user can specify a combustor geometry in terms of primary, intermediate and dilution zone volumes as well as the mass flow distribution of a given combustor design. HEPHAESTUS has previously been adopted in several aircraft trajectory optimization studies for example in (Ref. 27). The details of numerical formulation and methodology employed for the purpose of emissions prediction has been extensively reported by the authors in the following reference (Ref. 23). Thus, further elaboration shall be omitted.

Description of integrated HECTOR framework

The architectural representation of the integrated tool adopted for the purpose of this study is illustrated in Figure 1. Each defined mission profile is translated into discrete segments based on user defined input values in terms of operational procedures (velocity, altitude, climb and decent rate) and geographical latitude and longitude. The initial All Up Mass (AUM) is equal to the sum of the Operational Empty Weight (OEW), the useful payload, and the on-board fuel supplies. The required amount of fuel for a given mission has to be initially assumed; therefore an initial guess is made for the weight of the on-board fuel supply which is then refined through an iterative process.

For each flight segment HECTOR calculates the engine power requirement, intake inlet conditions, and updates the new space-wise position of the helicopter. TURBOMATCH subsequently establishes the engine's operating point to meet the power demand required and establishes the fuel flow and corresponding combustor inlet pressure, temperature and mass flow. This information is then utilised by the emissions model HEPHAEUSTUS to compute the corresponding emissions inventory of NO_x for the imposed flight segment.

The time-dependent fuel consumption at time t along with the respective emissions inventory, is then updated by applying a numerical time integration scheme on the time-variations of engine fuel flow and emission indices from zero up to the current mission flight segment. The calculated value of fuel burn is then subtracted from the initial AUM in order to account for the gradual weight reduction during the course of the mission. The overall process is re-iterated in a fixed-point manner until convergence is obtained for the total mission fuel burn.

A detailed description of the numerical integration of engine performance model (TURBOMATCH) and emissions model (HEPHAESTUS) with HECTOR has been separately reported by the authors in the following reference (Ref. 23). Thus, further elaboration shall be omitted.

Compilation of rotorcraft and engine configuration

The aircraft deployed for the purpose of this study is modeled after the Airbus Helicopeters Bo105 helicopter. The Airbus Helicopeters Bo105 is a TEL utility multipurpose helicopter equipped with two Rolls Royce Allison 250C20B turboshaft engines rated at 313 kW maximum contingency power.

Table 1 presents the rotorcraft model characteristics. The flight dynamics and trim analysis in terms of main rotor power required, collective pitch, lateral cyclic pitch and longitudinal cyclic pitch for reference Bo105 rotorcraft along with its validation with the flight test data has been separately reported by the authors in (Refs. 21-24).

The Allison 250C20B engine is equipped with a single-spool gas generator including a six-stage axial compressor followed by a centrifugal compressor. The engine configuration is outlined in Table 2. The maximum contingency power setting is selected as the design point for the respective TURBOMATCH model. The model has been matched at design point conditions with public domain data (Ref. 28) in terms of SFC. A detailed description of the Allison 250C20B engine family can be found in (Ref. 28).

Case study definition

Specifically tailored reference missions were designed and scheduled in HECTOR for the execution of the parametric studies. In total six missions were defined in terms of (Altitude, Speed, Time) corresponding to various mission ranges (e.g. 50 nautical miles to 300 nautical miles) the respective profiles corresponding to all six missions are presented in Fig. 3. To avoid repetition, Figs. 4 and 5 presents a comparison between mission altitude and cruise speed as a function of mission time for rotorcraft with MLF mission approach compared to CF mission approach. The incorporated operational procedures in terms of deployed airspeed, altitude, climb/descent rates and idle times have been defined with input from the European Helicopter Operator's Committee and were maintained fixed between both approaches.

The scheduled missions represent typical rotorcraft missions originating from point (A) and landing at point (b), for the purpose of demonstration and analyses the aforementioned approach is classed as CF mission approach. With regards to the MLF mission, an additional landing point is added precisely at midpoint of the mission range e.g. at 150 nmi for 300 nmi mission as illustrated in Fig. 2. In the MLF mission approach, the initial All-Up-Mass (AUM_i) of the rotorcraft is reduced by only carrying the amount of fuel required to reach mission midpoint. Additional refuelling is carried out during the mission midpoint landing phase for the remaining half of the mission.

Derivation of Reference rotorcraft weight classification
In order to successfully execute the parametric studies corresponding to both MLF and CF mission approach. The weight classification of the reference rotorcraft needs to be defined and established. The percentage breakdown of various parameters corresponding to Empty Weight (EW), Standard Fuel Tank (SFT), Operational Empty Weight (OEW) and Useful Payload (UPL) are tabulated in Table 3. During the analyses all aforementioned parameters were fixed, apart from UPL and the amount of required onboard fuel.

Furthermore, in order to enable the precise simulation of the MLF mission approach. The amount of fuel required corresponding to each reference mission needs to be first established based on the CF approach. To do this, all six reference mission were first simulated for various UPL values (e.g. 0%, 50%, and 100%). Figure 6 presents the change in reference rotorcraft AUM_i as a function of mission range for all simulated UPL values. It is to be noted that, in Fig. 6 the increase in AUM_i corresponding to each UPL value is predominantly influenced due to increase in the amount of on-board fuel required for a given mission. For 0% UPL the required on-board fuel for 50 nmi mission, based on the simulation is 66.27 kg and reaches a value of 365.33 for a 300 nmi mission as tabulated in Table 4. Table 4 also presents parameters (i.e. EW, fuel reserve etc.) that were used to derive the AUM_i of the reference rotorcraft and subsequently its corresponding fuel burn for a given reference mission.

RESULTS AND DISCUSSION

Conventional flying mission approach Results
Figure 7 presents the mission fuel burn and NO_x emissions for a range of UPL values as a function of mission range, based on the simulation of reference missions following a CF mission approach. Almost a linear trend is observed for both fuel burn and NO_x emissions corresponding to each UPL value. In Fig. 8 ΔMFB and ΔNO_x are presented for UPL of 50% and 100% relative to 0% UPL as function of mission range.

It can be established from Fig.8 that when increasing the UPL from 0% to 50%, the mission fuel and NO_x delta are increased by the order of 8% and 12.9% for 50 nmi mission and further increase up to 10.3% and 15% for 300 nmi mission. Similarly, when increasing the UPL from 0% to 100% results in mission fuel and NO_x delta of the order of 19% and 29.4% for 50 nmi mission and further increases up to 22% and 32.7% for 300 nmi mission.

Figure 9 presents the correlations for required engine power, fuel flow and NO_x emissions production rate as a function of mission time for reference 300 nmi mission corresponding to all three simulated UPL cases. The idle segments can be distinguished as conditions associated with low values of engine shaft power, fuel flow and NO_x. Climbing, forward flight along with hover are identified as the most demanding trim settings in terms of engine shaft power, and therefore have relatively higher demand in terms of fuel flow and NO_x emissions production rate. It is evident from Fig. 9 that the onboard UPL has a significant effect on the rotorcraft trim setting in terms of required engine power, this is predominantly attributed due to the fact that the UPL has a proportional effect on the rotorcraft AUM_i. The rotorcraft operates on significantly higher engine power, therefore higher fuel flow demand and higher NO_x production rate for all flight conditions except the idle condition where the required power is fixed for all cases at 20% of installed engine power.

Multiple-landing flying mission approach Results
Upon the successful completion of the simulations for reference missions corresponding CF mission approach. The derived fuel burn values tabulated in Table 4 can now be implemented to proceed with MLF mission approach simulations corresponding to all reference missions. The first step is to re-define the AUM_i for reference rotorcraft based on the fuel burn values established through the CF mission approach. To enable this, it was deemed practical to assume that, to fly a given reference mission through MLF approach, the AUM_i of the rotorcraft for given reference mission can be reduced by half of its required fuel burn value derived using the CF mission approach. Since during the MLF approach the remaining half of the required mission fuel refueling is assumed to be carried out during the mid-point landing phase.

Figure 10 presents the comparison between AUM_i for a wide range of UPL values corresponding to both mission approaches. It is evident that the rotorcraft with MLF mission approach has lower AUM_i corresponding to all missions compared to CF mission approach, and that the reduction in AUM_i becomes more predominant as a function of mission range. This is attributed to the fact that the required fuel burn increases almost linearly as function of mission range as elaborated in previous section and depicted in Fig. 7. Which in turn favors a greater reduction in AUM_i of the rotorcraft employing MLF mission approach.

Figure 11 presents the percentage detla for mission fuel burn and mission NO_x for a wide range of simulated UPL values corresponding to MLF mission approach relative to CF mission approach. Several interesting observation can be drawn from the characteristics of the trends presented in Fig 11. Firstly, it is interesting to note that for a given UPL value and reference mission, while the AUM_i of the rotorcraft with MLF approach is considerably lower compared to rotorcraft with CF mission approach as shown in Fig. 10. It does not necessarily proof a favorable effect on neither mission fuel burn nor NO_x emissions. This is predominantly attributed to the fact that, the amount of fuel burnt and NO_x emissions produced during the additional mission mid-point landing phase (associated with MLF approach) outweighs the amount of fuel and NO_x reduction attained from MLF approach throughout the entire mission.

Secondly, due to the aforementioned reason, each UPL value therefore corresponds to a break-even point (highlighted by black dots in Fig. 11) in terms of range. Where the penalty of additional fuel burn and NO_x emissions arising from additional mid-point landing procedure is equally compensated by the amount of fuel burn and NO_x reduction achieved throughout the entire mission. It can be therefore said that, the level of benefit that can be realized from the employment of MLF mission approach is strongly dependent on the mission range. Also, based on the results presented in Fig. 11 it can be concluded that for a typical TEL rotorcraft operating under a representative single-leg 300 nmi mission (A to B) carrying 100% payload. The employment of MLF mission approach has the potential to reduce mission fuel burn and NO_x emissions by the order of 4,65% and 7.97 respectively. The aforementioned benefit can be realized in exchange for a trade-off in mission total time of the order of (7.33 minutes OR 4.5%), imposed due to additional mid-point landing procedure as detailed in Fig 12.

In addition to the potential reduction for mission fuel burn and NO_x emissions, the results also suggest potential for further benefits in terms of rotorcraft engine maintenance and towards the enhancement of overall engine life. This argument is primarily supported based on the fact that, during the MLF mission approach the rotorcraft operates on a significantly lower engine power, therefore the engine OPR, combustor entry temperature, mass flow, rotational speed and the turbine entry temperature for the entire mission duration. A comparison between the both mission approaches for aforementioned engine parameters is presented in Fig. 13 and 14. It can be observed that the rotorcraft employing MLF mission approach operates on relatively lower temperatures and rotational speeds. Such operation of the engine can potentially improve the rate at which the engine components (compressor, combustor, and turbine) may deteriorate, thus can proof further benefit in terms of overall engine life compared to the rotorcraft-engine operating under CF mission approach.

CONCLUSIONS

This paper has successfully demonstrated the implementation of an integrated rotorcraft multidisciplinary simulation framework, deployed for the comprehensive assessment of combined rotorcraft–powerplant systems performance at mission level. The proposed methodology comprises a wide-range of individual modelling theories applicable to rotorcraft performance and flight dynamics, gas turbine engine performance, and estimation of gaseous emissions (i.e. nitrogen oxides). The overall methodology has been successfully deployed to conduct a comprehensive mission level feasibility study for a twin-engine light (TEL) rotorcraft, modeled after the Airbus Helicopters Bo105 configuration operating on a multiple-landing flying mission approach (MLF) compared to rotorcraft employing a conventional flying (CF) mission approach.

The results of the analyses allow mission level assessment of the both aforementioned approaches for a wide-range of useful payload (UPL) values, mission range as well as mission level outputs e.g. fuel burn, mission time, and gaseous emissions (i.e. NO_x). Furthermore, evaluation of engine cycle parameter (i.e. overall pressure ratio (OPR), turbine entry temperature (TET) and total engine mass flow) have also been performed with respect to both approaches.

The results acquired through the parametric analyses suggest that the MLF mission approach has the potential to significantly reduce rotorcraft mission fuel burn as well as gaseous emission (i.e. NO_x). Furthermore, it has been demonstrated through the acquired results that for a representative TEL rotorcraft operating with 100% payload on a single-leg mission (A to B) with a range of 300nm. The employment of MLF mission approach can potentially reduce the mission fuel burn and NO_x emissions by the order of 4.65% and 7.97% compared to rotorcraft operating under CF mission approach. The aforementioned benefit is however realized in exchange for a trade-off in mission total time of the order of (7.33 minutes OR 4.5%), imposed due to additional mid-point landing procedure associated with MLF approach.

It has also been established through the acquired results that rotorcraft employing the MLF mission approach requires lower engine operating power throughout the entire mission duration, and therefore operates on a relatively lower engine OPR, combustor entry temperature, mass flow, rotational speed and the turbine entry temperature compared to rotorcraft employing CF mission approach. It has been emphasized that such operation of the rotorcraft engine can potentially improve the rate at which the engine components (compressor, combustor, and turbine) may deteriorate, thus the MLF mission approach can potentially proof further benefit in terms of engine maintenance and overall engine life. Finally it has been emphasised that the total mission range is a critical parameter in determining the level of benefit that can be attained from the employment of MLF mission approach. The proposed methodology constitutes an enabling technology for the evaluation of existing and conceptual rotorcraft in terms of operational performance and environmental impact at mission level.

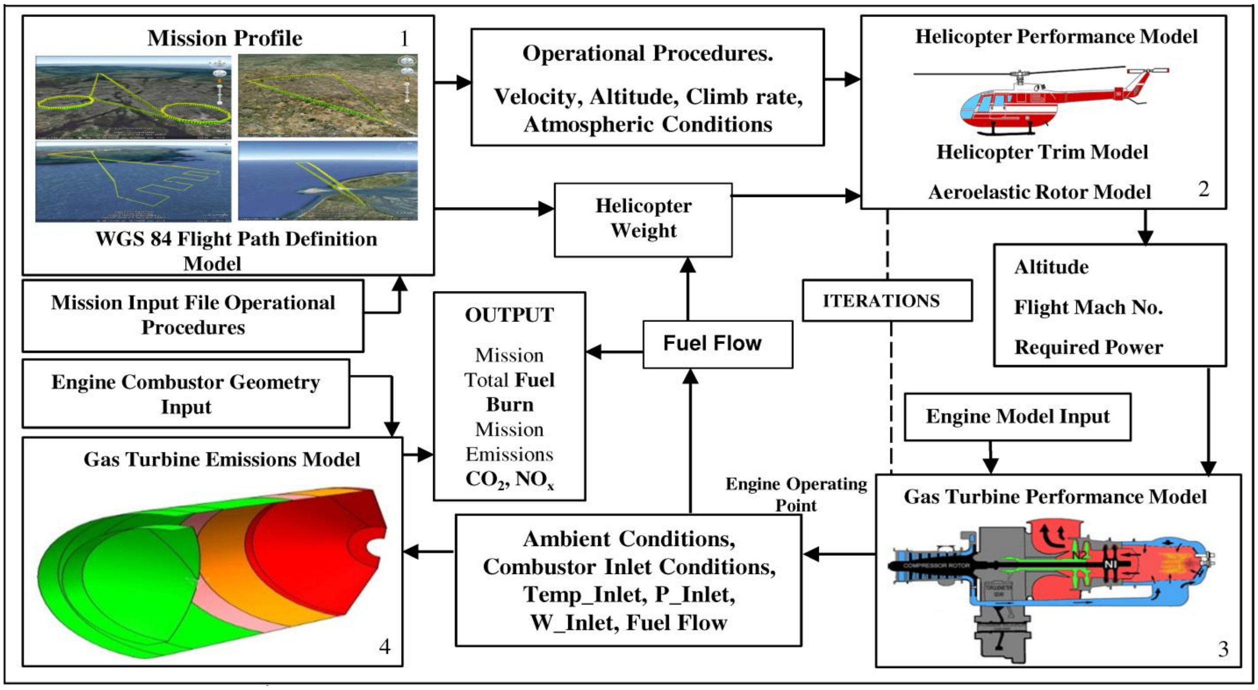

Figure 1: HECTOR; Architecture of integrated rotorcraft multidisciplinary simulation framework.

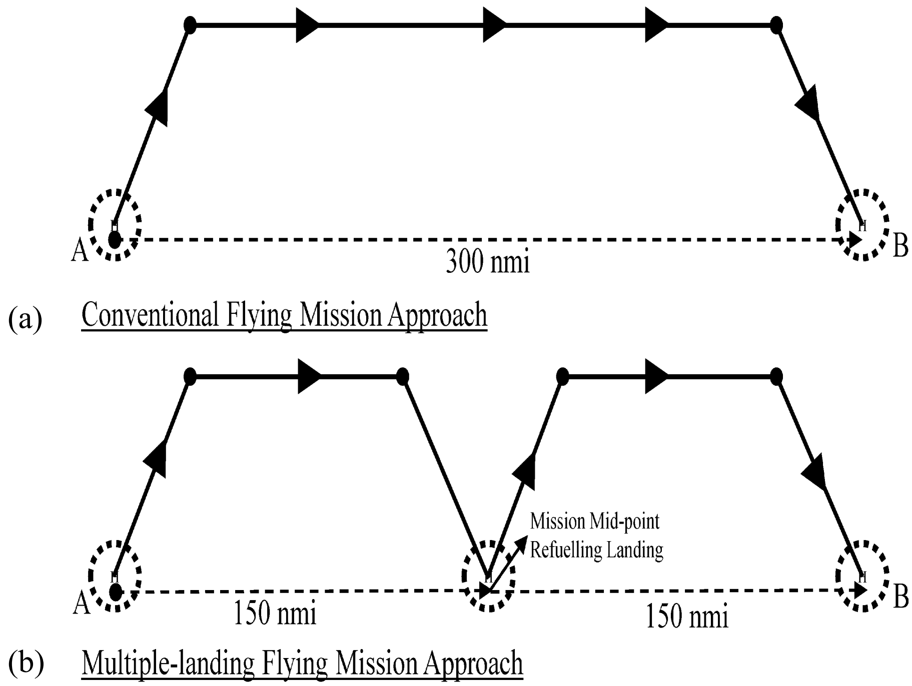

Figure 2: Illustration of typical single-leg (A to B) mission profile: (a) CF mission approach, (b) MLF mission approach.

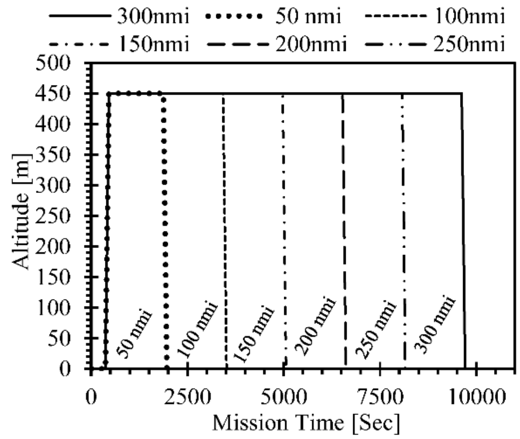

Figure 3: Reference missions profiles: time variation of deployed operational AGL altitude.

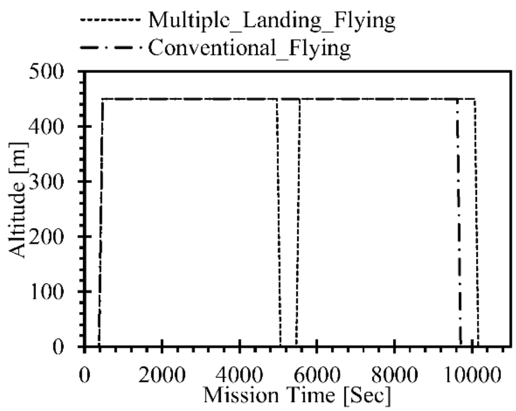

Figure 4: Reference 300nmi mission profile: a comparison between the deployed operational AGL altitude for CF and MLF mission approach.

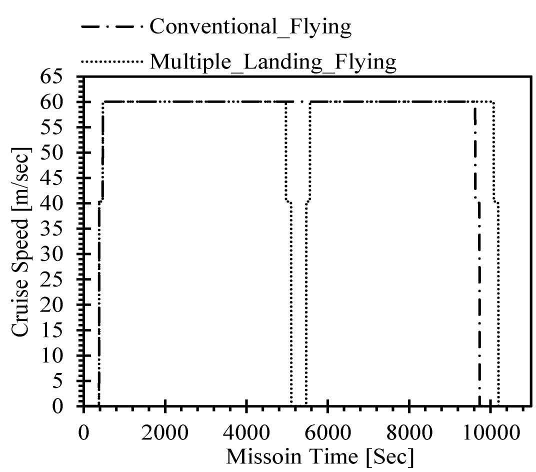

Figure 5: Reference 300nmi mission profile: a comparison between the deployed operational airspeed for CF and MLF mission approach.

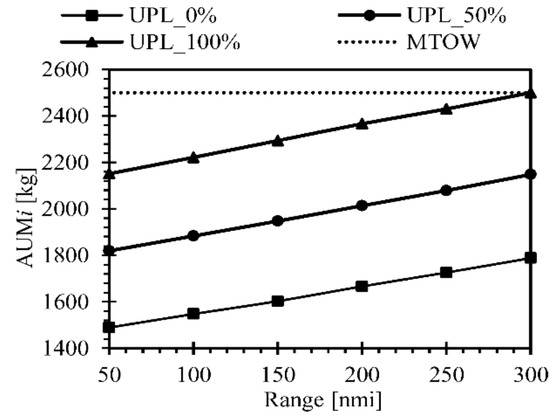

Figure 6: Effect of required onboard fuel as function of mission range on initial all-up-mass of reference rotorcraft.

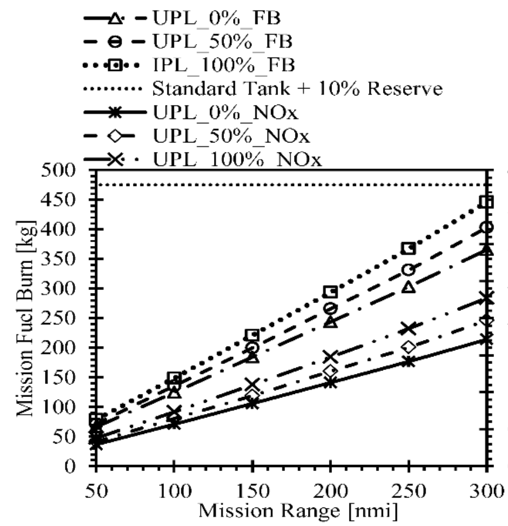

Figure 7: Results for MFB and NO_x emissions: reference rotorcraft employing CF mission approach.

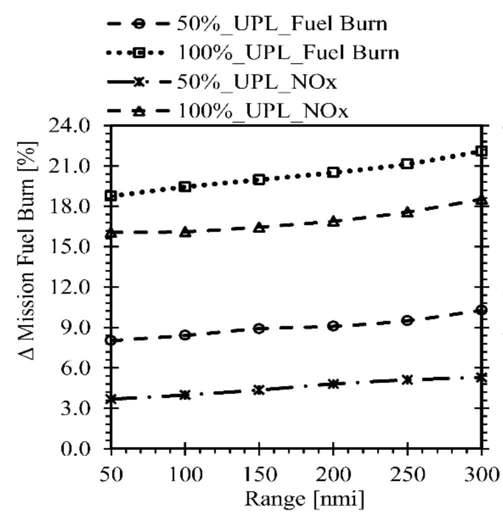

Figure 8: ΔFB and ΔNO_x emissions relative to 0% UPL: reference rotorcraft employing CF mission approach.

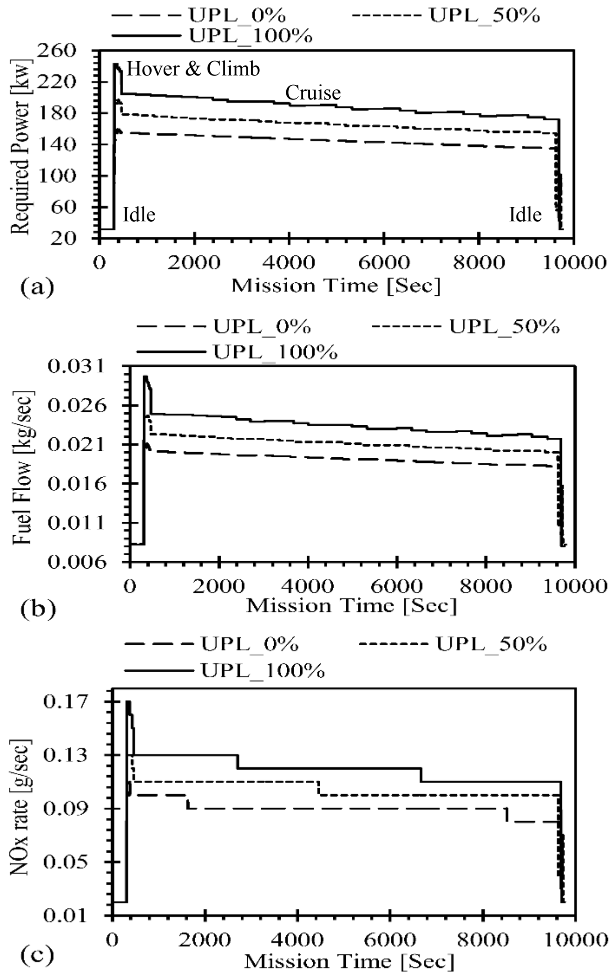

Figure 9: Engine performance parameters for reference rotorcraft employing CF mission approach, reference 300 nmi mission: (a) shaft power, (b) fuel flow, (c) NO$_x$ emission production rate.

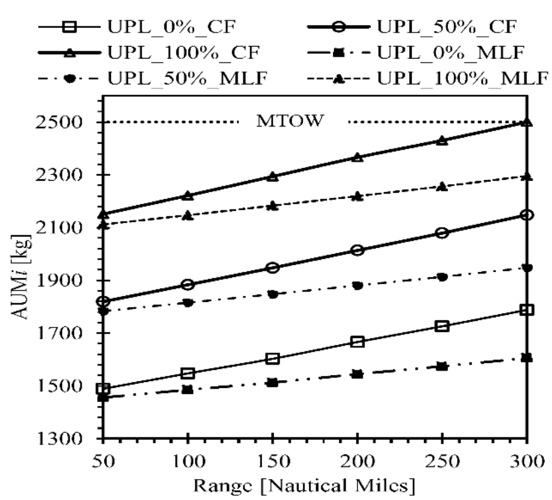

Figure 10: Comparison of initial all-up-mass for reference rotorcraft employing CF and MLF mission approach.

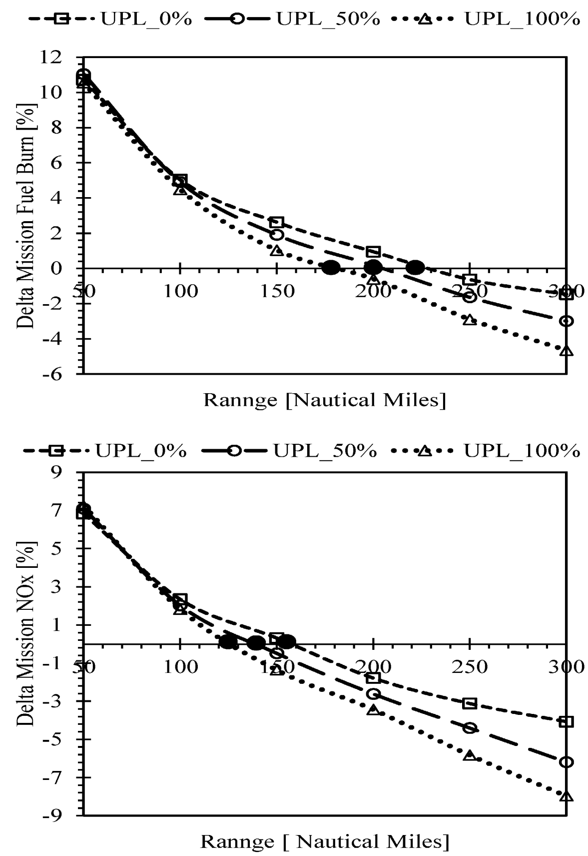

Figure 11: ΔFB and ΔNO$_x$ emissions for reference rotorcraft employing MLF approach relative to CF mission approach.

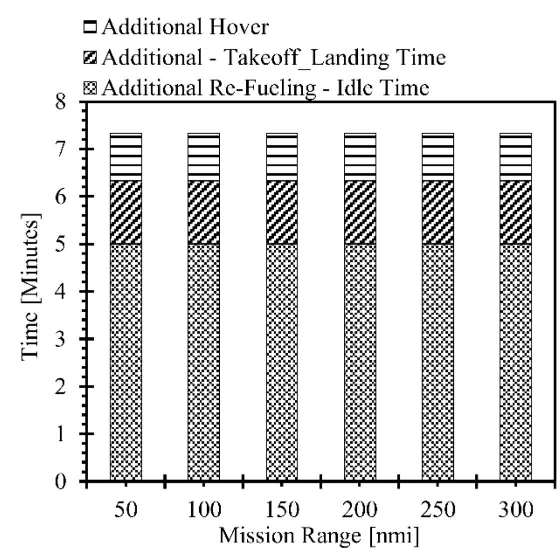

Figure 12: Classification of time penalty associated with MLF mission approach.

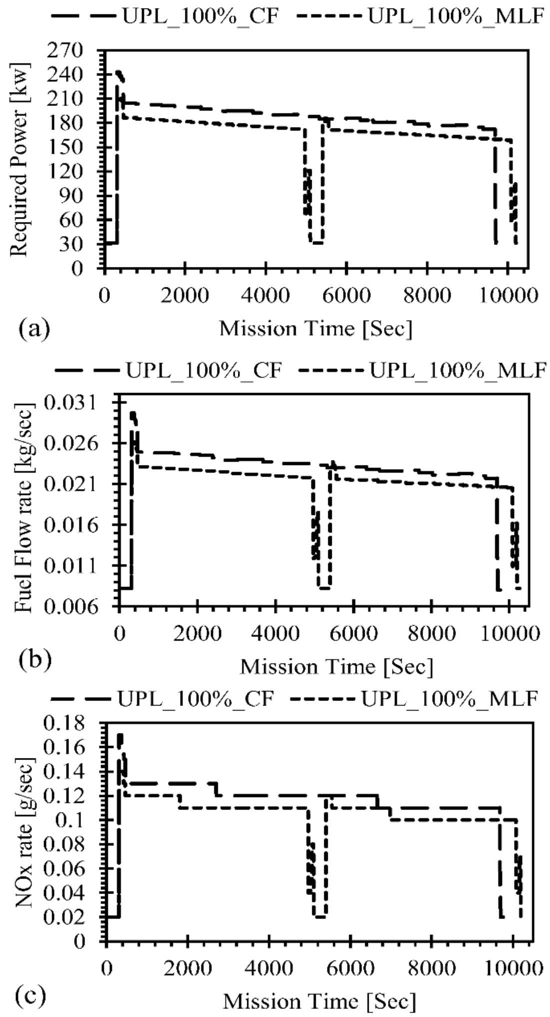

Figure 13: Comparison of engine performance parameters between reference rotorcraft employing CF and MLF mission approach, reference 300 nmi mission: (a) shaft power, (b) fuel flow, (c) NO_x emission production rate.

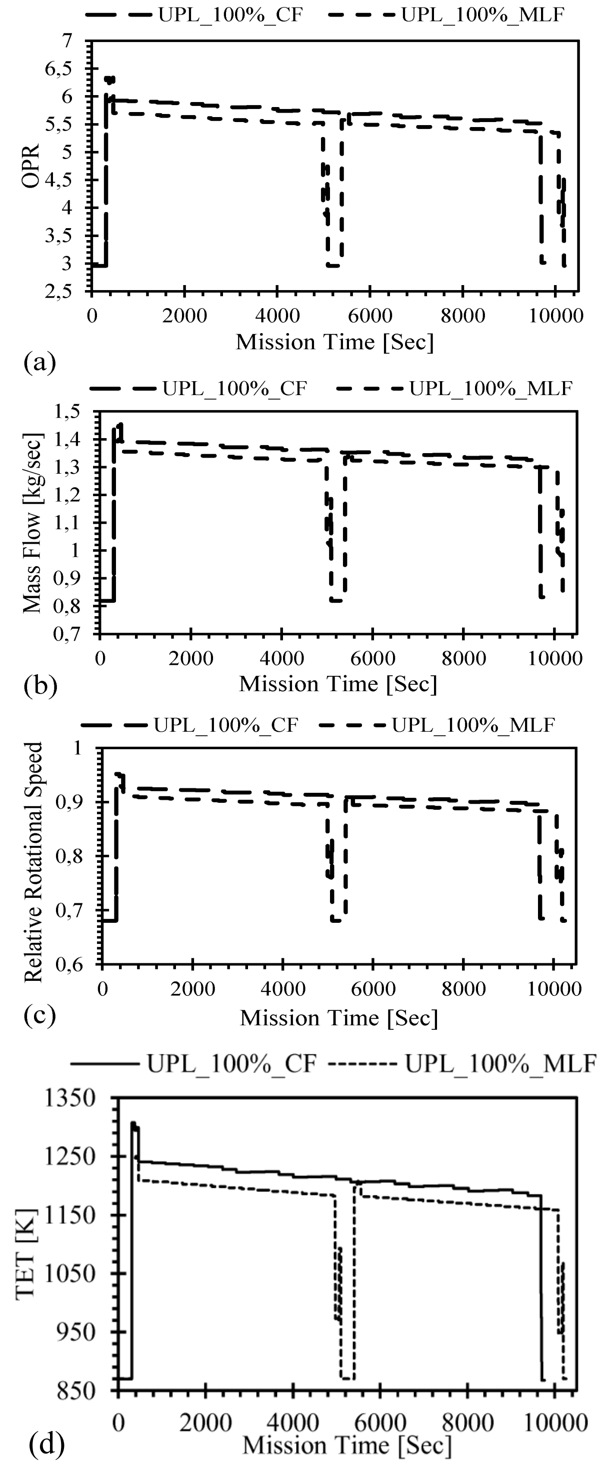

Figure 14: Comparison of engine performance parameters between reference rotorcraft employing CF and MLF mission approach, reference 300 nmi mission: (a) OPR, (b) $\dot{W}$, (c) relative rotational speed, (d) TET.

Table 1: Baseline design parameters: Reference Bo105 twin-engine light rotorcraft configuration.

Design Parameter	Value	Units
Max Gross Weight	2500.00	kg
OW	2200.00	kg
Number of blades	4.00	-
Blade chord	4.91.00	M
Blade twist	8.00	Degree
Rotorspeed	44.40	Rad/sec

Table 2: Baseline design parameters: Reference Bo105 twin-engine light rotorcraft engine.

Design Parameter	Value	Units
TET	1470.00	K
W	1.56	Kg/sec
LPC PR	2.73	-
HPC PR	2.60	-
DP shaft power	313.00	kW
DP SFC	109.98	μg/J

Table 3: Reference rotorcraft weight classification.

Parameter	%MTOW	Weight [kg]
EW	55	1375.00
STank	19	475.00
OEW	74	1850.00
UPL	26	650.00
MTOW	-	2500.00

Table 4: Reference missions parametric analyses results; reference rotorcraft employing CF mission approach.

UPL 0%						
Payload	**UPL[kg]**	**RM[nmi]**	**MFB[kg]**	**EW[kg]**	**AUM*i*[kg]**	**FRV[kg]**
0%	0.00	50.00	66.27	1375.00	1422.50	47.50
0%	0.00	100.00	124.60	1375.00	1422.50	47.50
0%	0.00	150.00	180.00	1375.00	1422.50	47.50
0%	0.00	200.00	243.60	1 375,00	1422.50	47.50
0%	0.00	250.00	303.11	1375.00	1422.50	47.50
0%	0.00	300.00	365.33	1 375,00	1422.50	47.50
UPL 50%						
Payload	**UPL[kg]**	**RM[nmi]**	**MFB[kg]**	**EW[kg]**	**AUM*i*[kg]**	**FRV[kg]**
50%	325.00	50.00	71.59	1375.00	1747.50	47.50
50%	325.00	100.00	135.60	1375.00	1747.50	47.50
50%	325.00	150.00	199.73	1375.00	1747.50	47.50
50%	325.00	200.00	265.72	1375.00	1747.50	47.50
50%	325.00	250.00	331.22	1375.00	1747.50	47.50
50%	325.00	300.00	400.27	1375.00	1747.50	47.50
UPL100%						
Payload	**UPL[kg]**	**RM[nmi]**	**MFB[kg]**	**EW[kg]**	**AUM*i*[kg]**	**FRV[kg]**
100%	650.00	50.00	78.70	1375.00	2072.50	47.50
100%	650.00	100.00	148.82	1375.00	2072.50	47.50
100%	650,00	150.00	221.07	1375.00	2072.50	47.50
100%	650.00	200.00	293.54	1375.00	2072.50	47.50
100%	650.00	250.00	367.17	1375.00	2072.50	47.50
100%	650.00	300.00	446.04	1375.00	2072.50	47.50

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Improvements in the rotorcraft fuel economy and environmental impact through multiple-landing mission strategy

Ali, Fakhre

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Ali F, Goulos I, Pachidis V, Improvements in the rotorcraft fuel economy and environmental impact through multiple-landing mission strategy, American Helicopter Society's 72nd Annual Forum and Technology Display, 17 - 19 May 2016, West Palm Beach, Florida, USA, pages 2463-2476

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